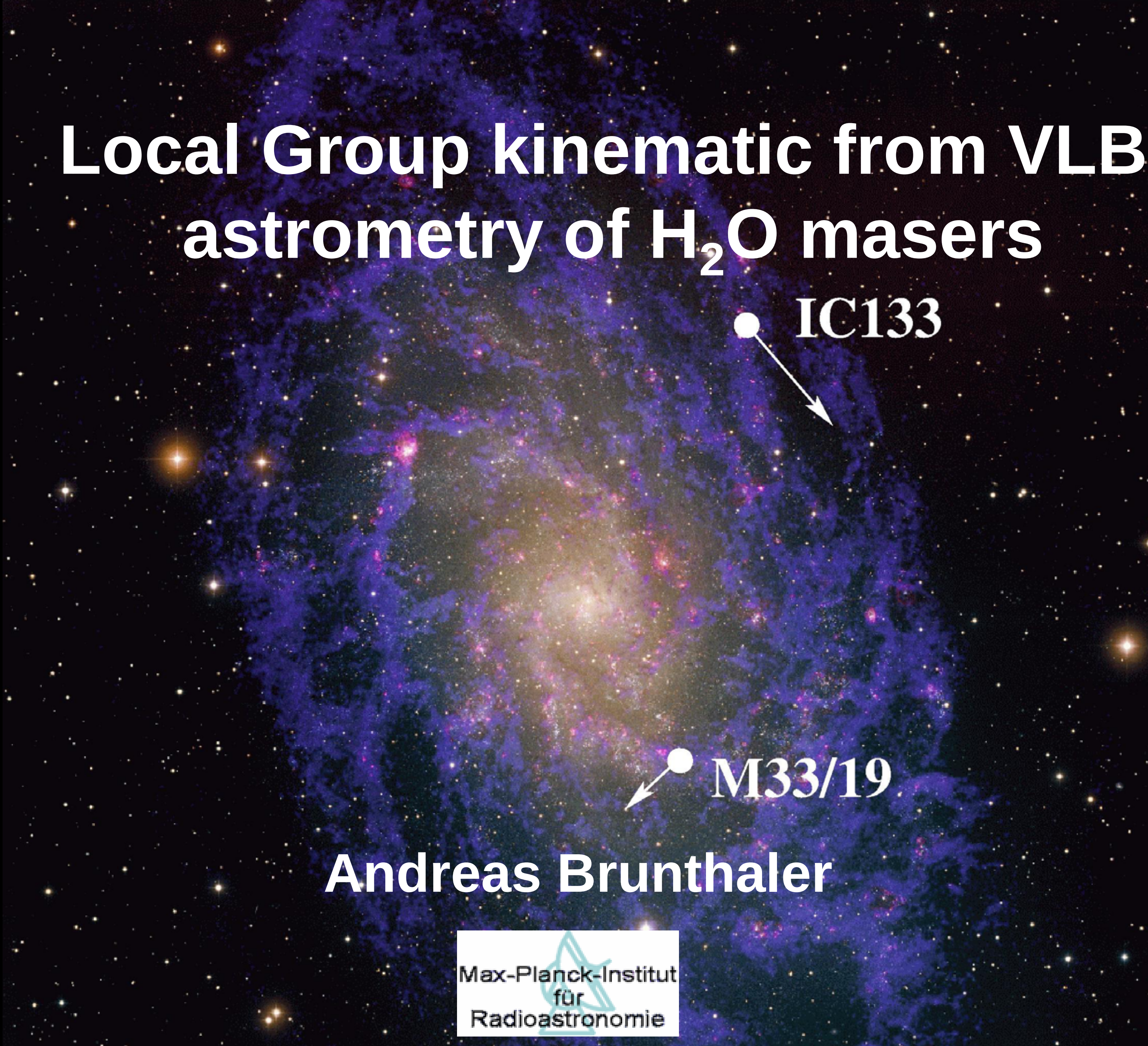
Local Group kinematic from VLBI astrometry of H_2O masers



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Radioastronomie

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Outline

- Introduction & Motivation
- Observing technique
  - Astrometry & Phase Referencing
- Observations & Results:
  - 3D Space Motion of M33
  - Geometric Distance to M33
  - 3D Space Motion of IC 10
- Summary & Outlook

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The Great Debate

ternal galaxies?

INVESTIGATIONS ON PROPER MOTION

TENTH PAPER: INTERNAL MOTION IN THE SPIRAL NEBULA MESSIER 33, N.G.C. 598[1]

By ADRIAAN VAN MAANEN

ABSTRACT

Measures of internal motion in the spiral nebula M 33 (N.G.C. 59 of two photographs taken in 1910 and 1922 by Ritchey and Huma gives, with respect to twenty-four comparison stars, the annual prop nebula, $\mu_\alpha = +0''.003$, $\mu_\delta = -0''.004$, and the motions of 399 nebular this motion. The internal motions are shown on Plate XIX. They c as a rotation or as a motion outward along the arms of the spira latter. Taken as a rotation, the motions indicate periods from 60,000

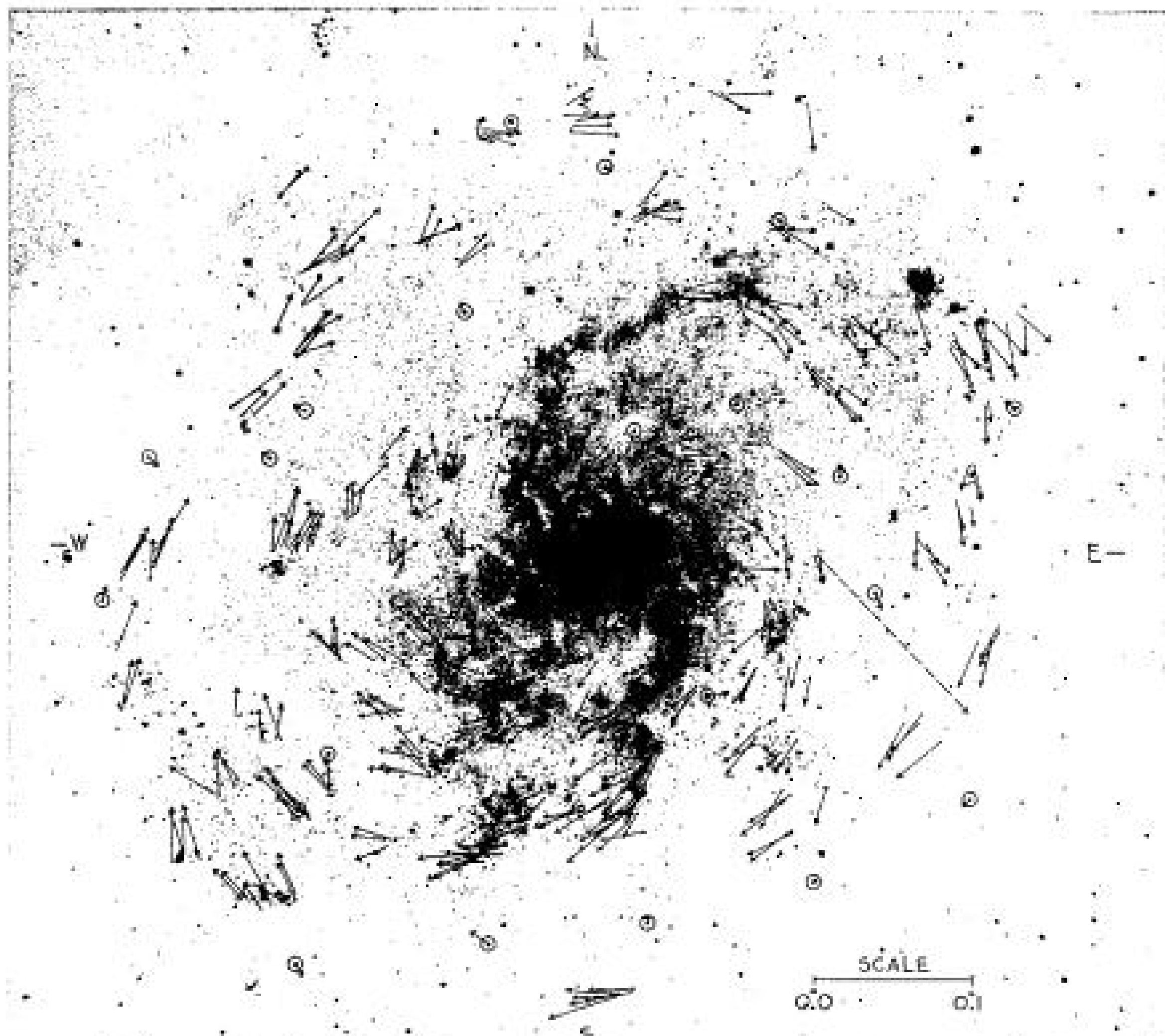
Reality of measured displacements in spirals.—A summary of the spirals, M 33, 51, 63, 81, 94, 101, and N.G.C. 2403, shows that the dis cannot have been caused by (*a*) the telescope, (*b*) the quality of th measuring instrument, (*d*) the measurer. Apparently they must be a senting actual internal motion. As such they are in agreement wi cosmogony lately proposed by Jeans.

Parallaxes of the larger spiral nebulae.—These seem to lie bet thousandths and a few thousandths of a second of arc. The corresp range from several light-years to several hundred light-years. The therefore enormous as compared with our solar system, but small in cor system of the Milky Way.

In 1921 a preliminary note on the internal motion i was published in the *Proceedings of the National Academ* it included measures of thirty nebulous points on two at the 25-foot focus of the 60-inch reflector and of twen on the photographs taken at the 80-foot focus of the ment. The measures were all made with the monoc ment of the Zeiss stereocomparator, while those plann hundred nebular points on the first pair of plates we until the new stereocomparator, then under construction ment shop of the observatory, should be completed. was finished, the plate taken by Mr. Duncan in 1920 tally broken by him and it was necessary to wait until a could be made. This was secured by Mr. Humason c

[1] *Contributions from the Mount Wilson Observatory*, No. 260.

[2] *Mt. Wilson Comm.*, No. 71.



The Great Debate

- 1920s: Are 'spiral nebulae' external galaxies?

  - Curtis: Yes!
  - Shapley: No!

- Hubble found Cepheids in M31!

- Motions and geometric distances of nearby galaxies is one goal of future astrometry missions (e.g. Gaia & SIM)

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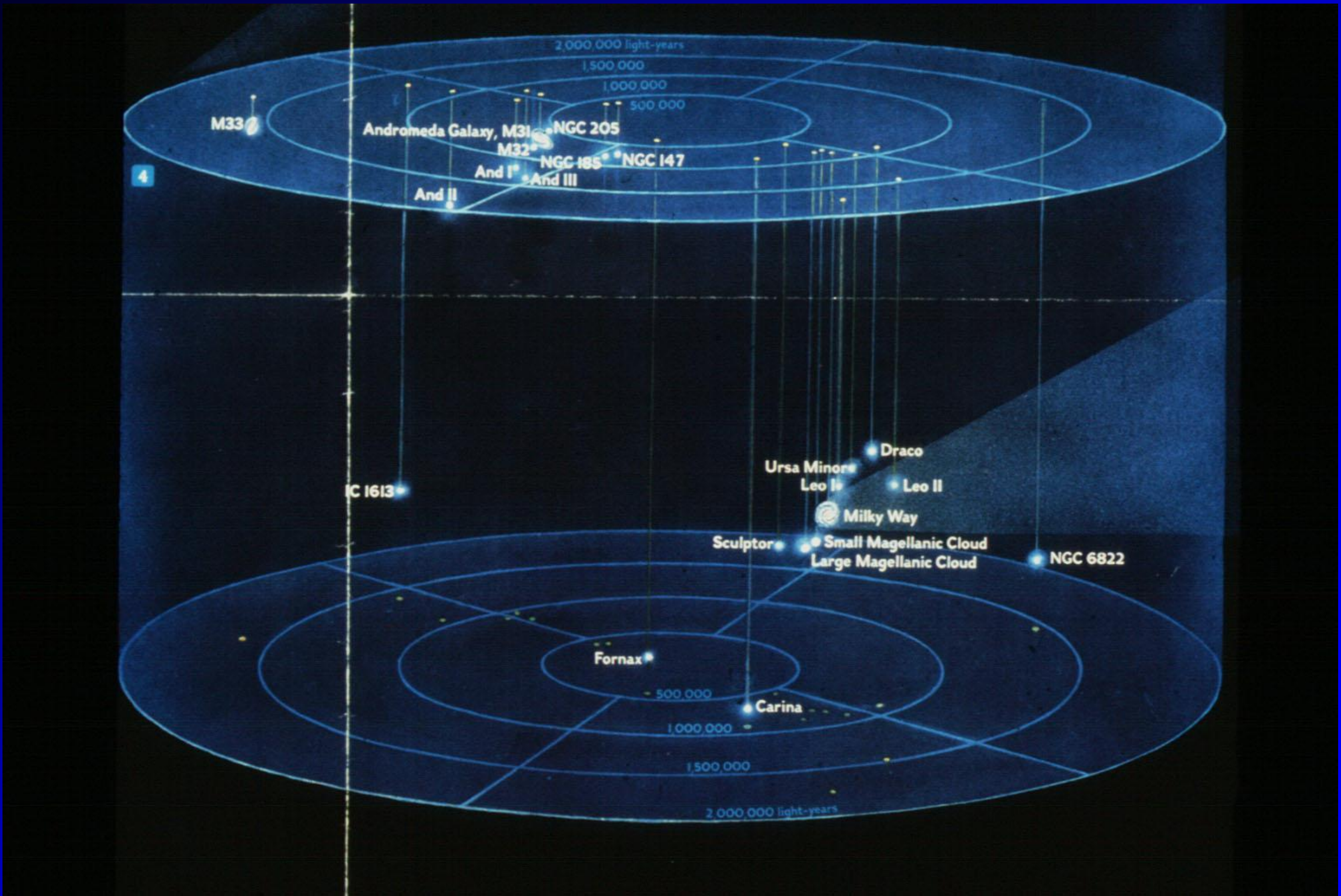
The Local Group of Galaxies



Dynamical models of the Local Group

- dynamics needed to estimate mass distribution
- only *radial* velocities of galaxies known

- Local Group Timing (Kahn & Woltjer 1959)

- Milky Way and Andromeda (M31) have probably formed nearby and completed the larger part of at least one orbit.

- Keplers law gives a mass of $> 2\times10^{12}$ M_{sol} for the Local Group assuming zero proper motion of M31

- dark matter needed

Dynamical models of the Local Group

- proper motions needed, but not easy:

Photographic plates (50 years): 0.56±0.25 mas/yr for Sculptor dwarf galaxy at 88 kpc (Schweitzer et al. 1995)

HST: 0.61 ± 0.23 mas/yr for Fornax dwarf at 140 kpc (Dinescu et al. 2004)
0.55 ± 0.23 mas/yr for Ursa Minor at 63 kpc (Piatek et al. 2005)
LMC (Kallivayalil et al. 2006)
SMC (Kallivayalil et al. 2006)
Canis Major (Dinescu et al. 2005)
Sagittarius dSph (Dinescu et al. 2005)
Carina dSph (Piatek et al. 2003)

- limited to closest neighbours of Milky Way (< 150 pc)
impossible for M31 subgroup

Expected proper motions of few 10 μas/yr detectable with VLBI

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VLBI Astrometry

- strong and compact radio sources needed

1. Radio cores
   - no strong cores in Local Group
   - $S_{8.4\ GHz}$(M31*) = 28±5 μJy (Crane et al. 1992)

2. strong maser emission
   - H_2O masers known in M33 and IC10
   - M33 and IC10 in Andromeda subgroup (~ 800 kpc)

VLBI Astrometry

- Which instrument, EVN or VLBA?

EVN:

- large telescopes
- large bandwidth

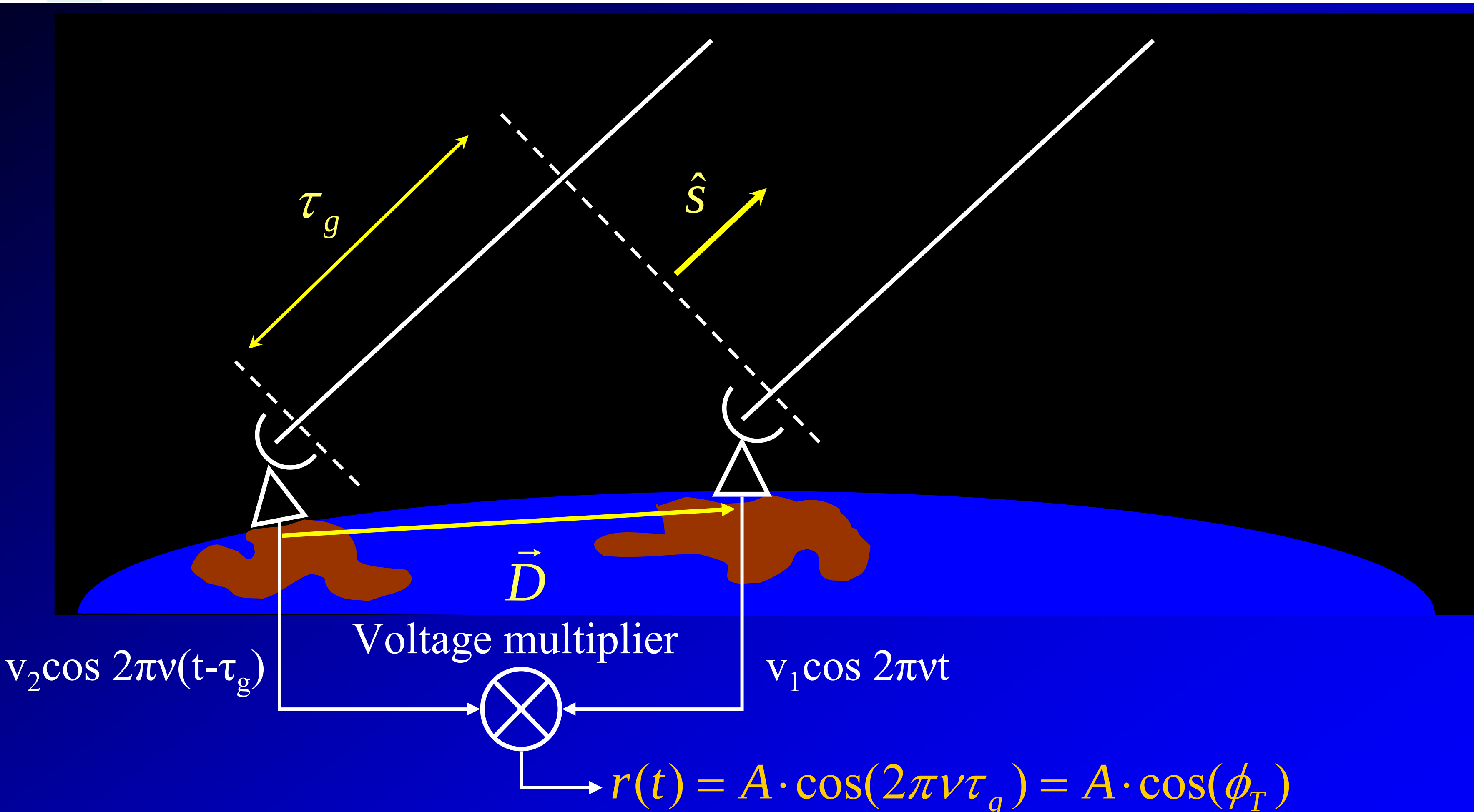
- slow telescopes
- fixed scheduling

VLBA:

- fast telescopes
- dynamic scheduling

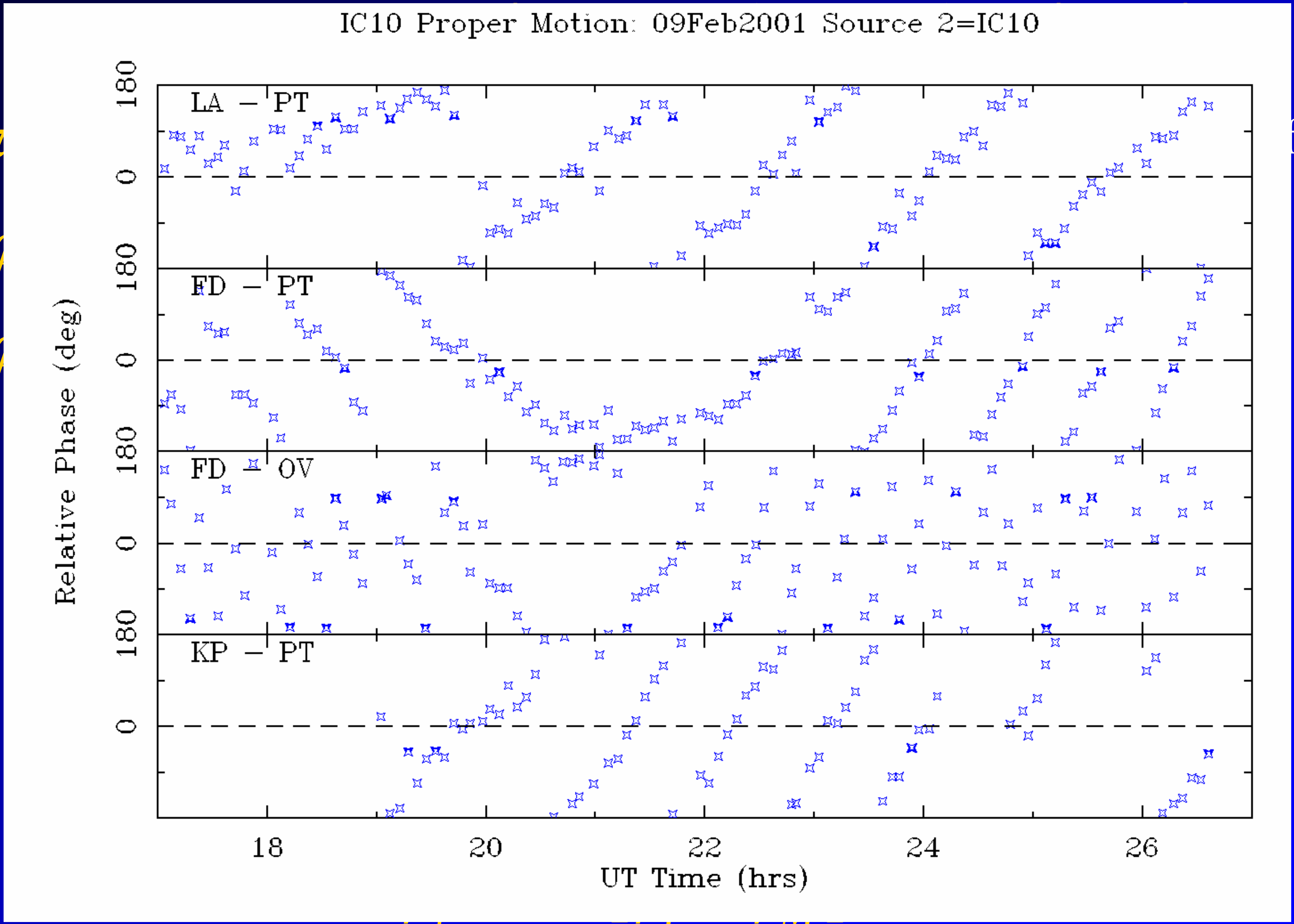
- small telescopes

VLBI Astrometry



Geometric Delay: $\tau_g = \dfrac{\vec{D} \cdot \hat{s}}{c}$

Phase referencing



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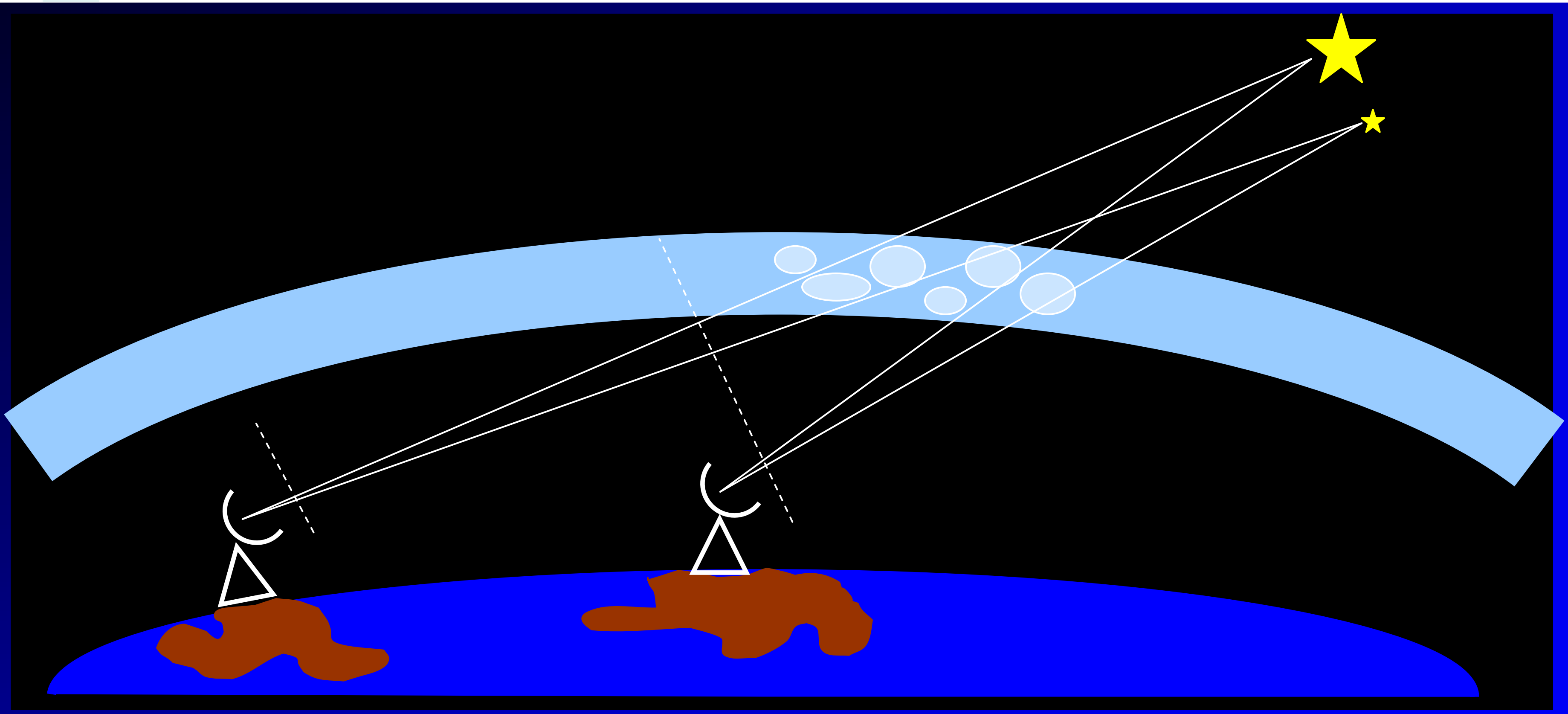
Phase referencing



- calibrate phase on nearby source with known position
- transfer phase calibration to target source

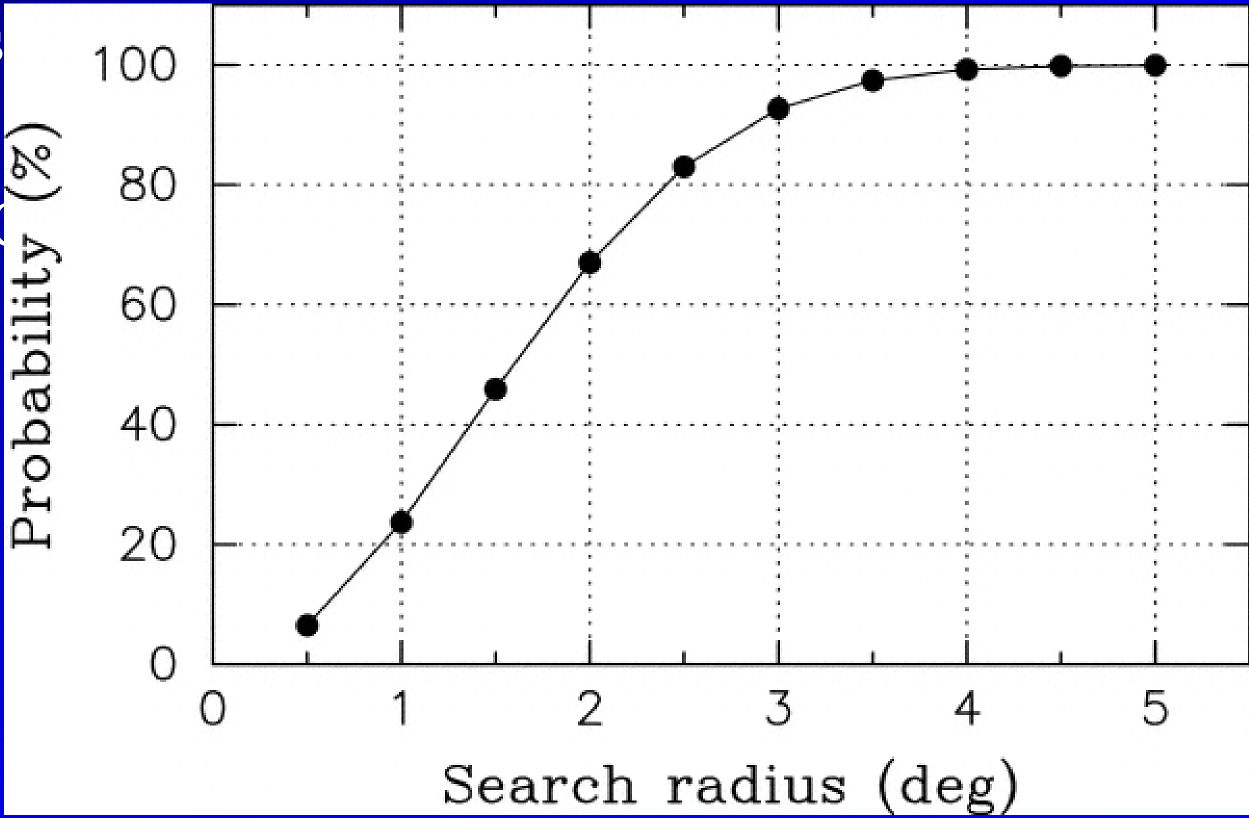
takes out most correlator-model errors, atmosphere etc.

VLBI Astrometry

Reference sources:

- most errors scale with the angular distance
- the closer the better
- nearby sources

1. ICRF, VLBA C



(VCS5; Kovalev et al 2007)

VLBI Astrometry

Reference sources:

- most errors scale with the angular distance
- the closer the better
- nearby sources also important check sources

1. ICRF, VLBA Calibrator Survey (VCS1-VCS5), etc.

2. Search yourself:
   - look for compact NRAO VLA Sky Survey (NVSS) sources
   - observe candidates at two frequencyies
   - choose compact sources with flat spectrum

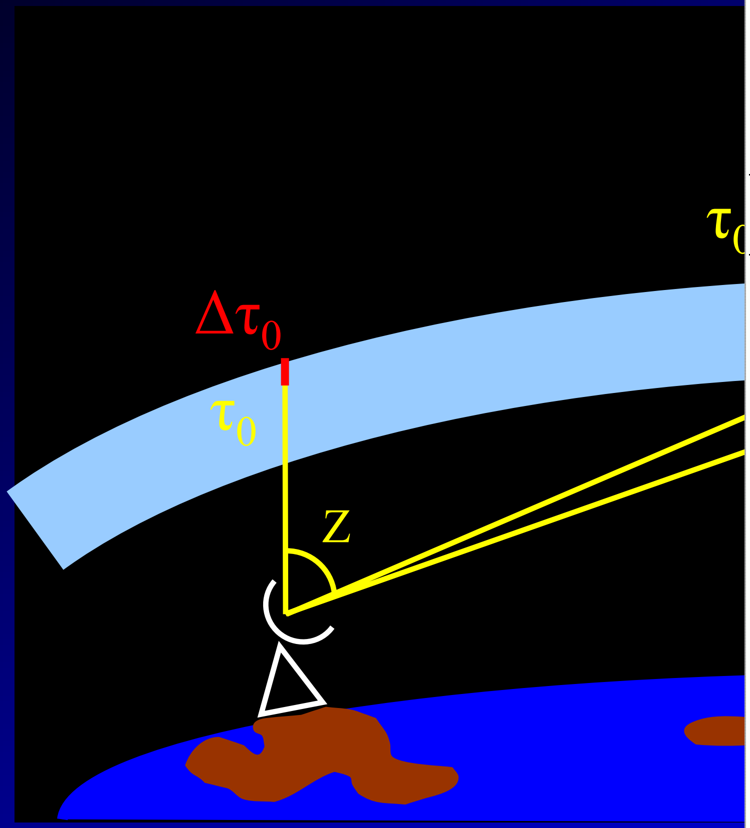
VLBI Astrometry

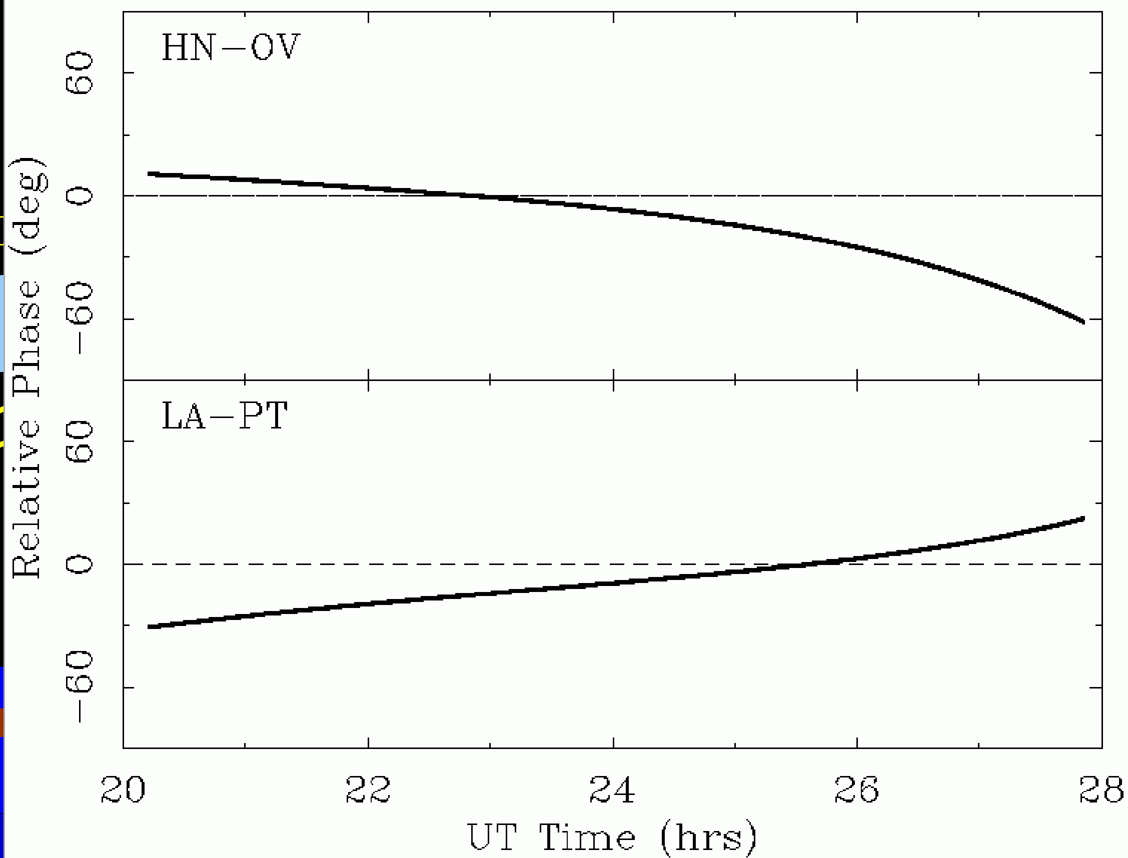
Theoretical astrometric accuracy:

$$\sigma_\theta = \frac{\theta_{beam}}{2 \times SNR} \qquad \theta_{beam} \approx 0.5 mas \qquad SNR \approx 25$$

$$\Rightarrow \sigma_\theta \approx 10 \mu as$$

VLBI Astrometry





Dominant source of error:

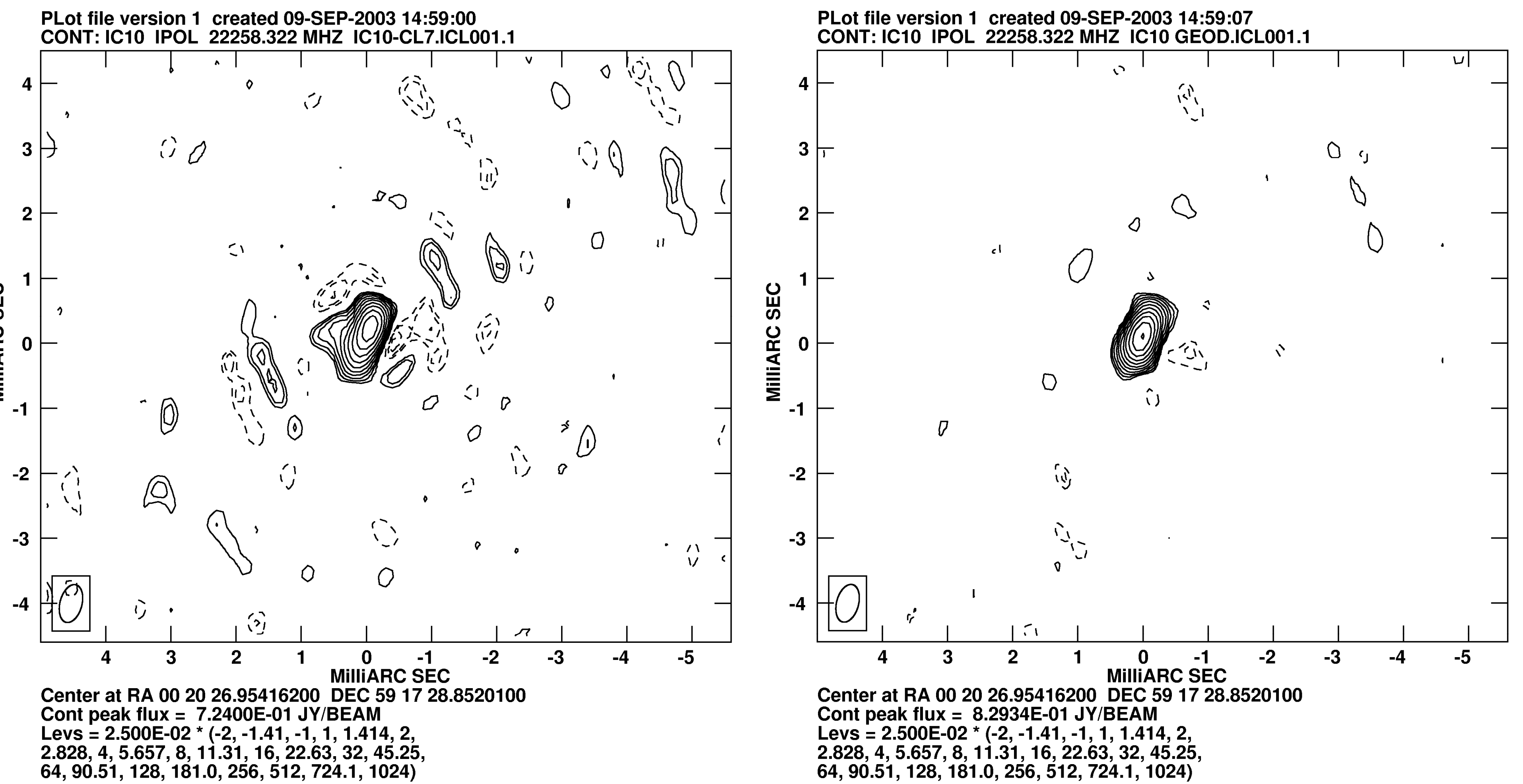
- inaccurate zenith delay τ_0 at each antenna in correlator-model
- different phase-errors for different sources

$$\Delta\varphi_1 = 2\pi\nu\cdot\Delta\tau_0 \sec(Z_1)$$
$$\Delta\varphi_2 = 2\pi\nu\cdot\Delta\tau_0 \sec(Z_2)$$

$\Rightarrow$ degrade image quality

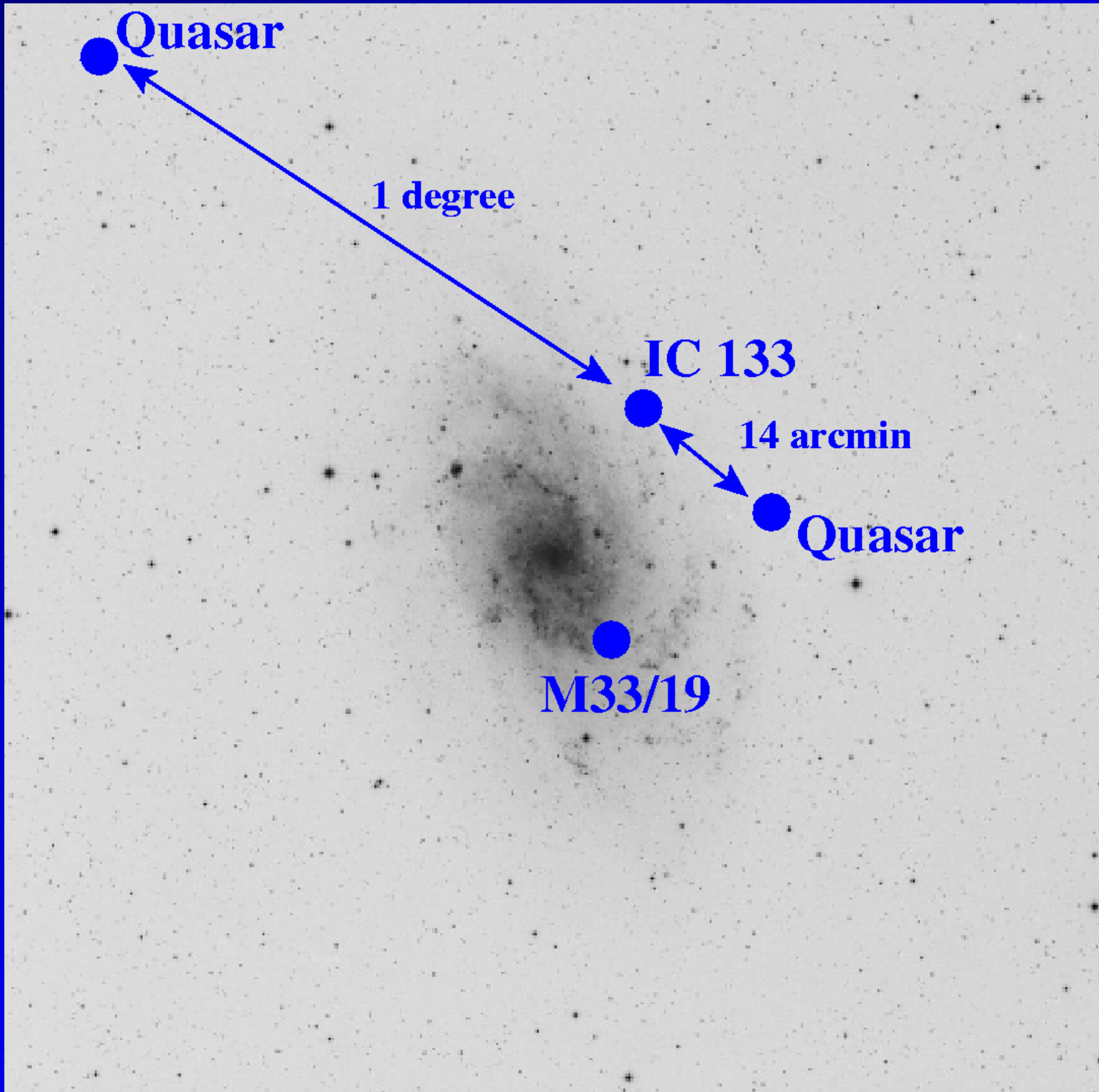
VLBI Astrometry

- Include geodetic-like observations



Observations of M33

- phase-referencing with VLBA
  - strong quasar 1° away
  - weak quasar 14’ away
  - two maser regions



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Observations of M33

- 12 hour observation

  1 hour geodetic obs.
  4.5 hours phase ref.
  1 hour geodetic obs.
  4.5 hours phase ref.
  1 hour geodetic obs.

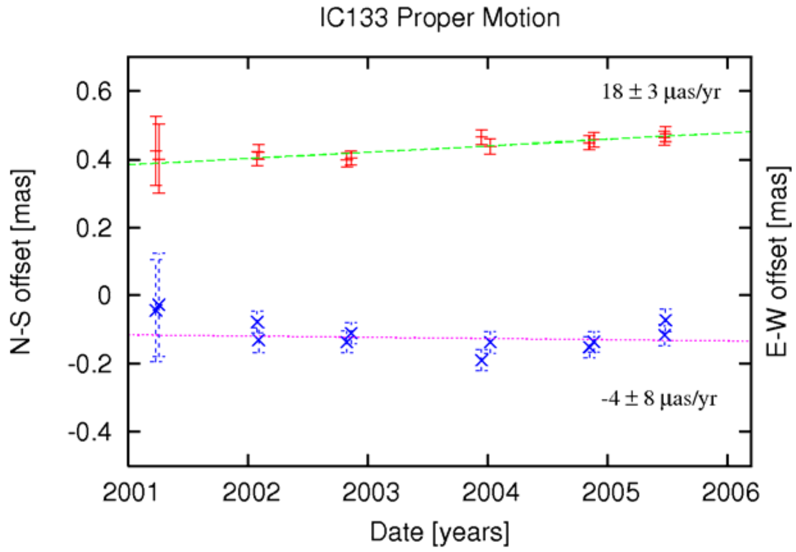
- Phase referencing: switching time 30s
  'Q1 – IC133 – Q1 – M33/19 – Q1 – Q2 – Q1'

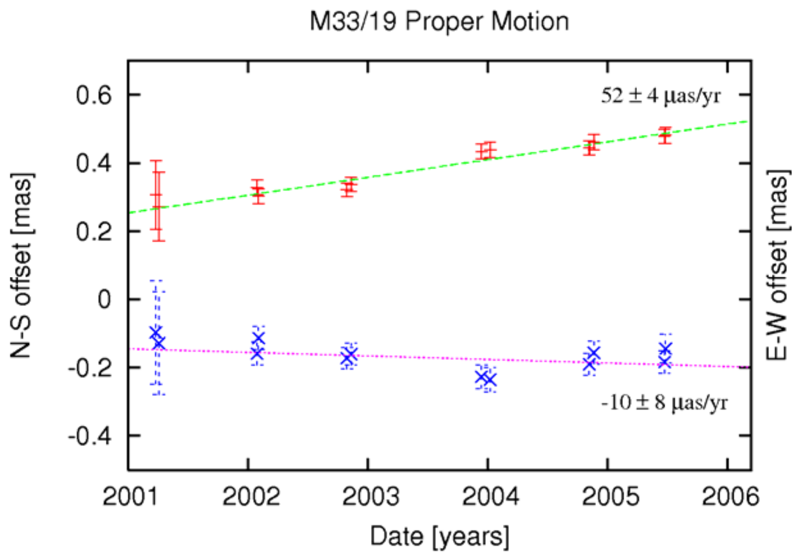
- channel spacing of 62.5 kHz ⇔ 0.84 km/s

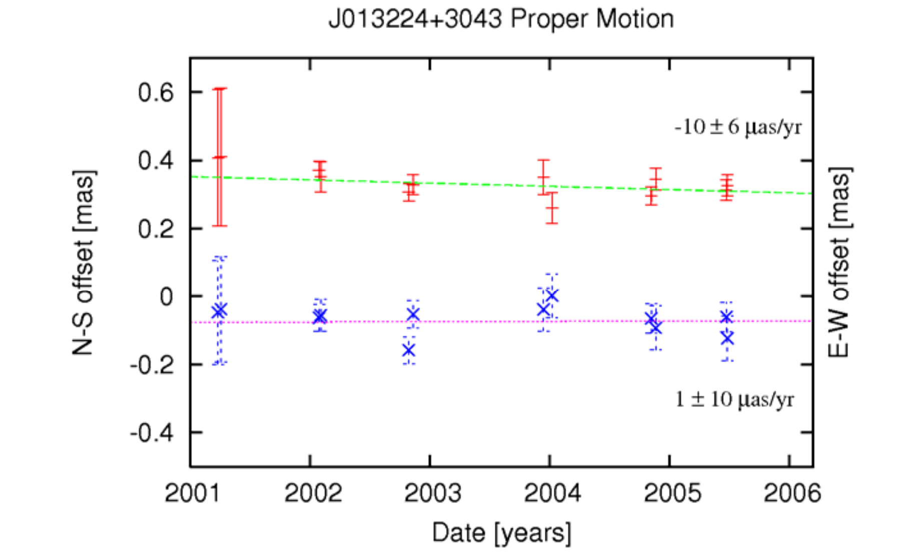
- **two** observations within a short time to **check** accuracy

Observations of M33

Use always the same observing str







Rotation of M33

Relative motion between IC133 and M33/19 depends <u>only</u> on rotation

Assume $v_{pec} < 20$ km/s (radial velocities of maser and H I agree)

<u>Rotation model of HI:</u>
(Corbelli & Schneider 1997)

<u>Relative proper motions</u>

In RA:	106.4 ± 20 km/s	⇔	29.9 ± 2 μas/yr
In DEC:	35.0 ± 20 km/s	⇔	9.7 ± 5 μas/yr

$v = D \cdot \omega$ ⇒ **D = 750 ± 140 ± 50 kpc**

Distance of M33

Reference	Method	Distance [kpc]
Lee et al. 2002	Cepheids (revised)	802 ± 51
Kim et al. 2002	TRGB + RC	916 ± 55
McConnachie et al. 2005	TRGB	809 ± 24
This work	rotational parallax	$750 \pm 140 \pm 50$

- Accuracy of < 10 % possible
  - better rotation model (higher resolution H I data)
  - new observations and third maser in M33

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Space motion of M33

- Proper motion: $\mathbf{v}_{prop} = v_{obs} - v_{rot} - v_{\odot}$

RA: $v_{prop} = (4.7 \pm 3) - (-18.5 \pm 6) - (53 \pm 3)$ µas/yr

$= -29.3 \pm 7.6$ µas/yr

$= -101 \pm 35$ km/s

DEC: $v_{prop} = (-14 \pm 6) - (-22 \pm 6) - (-38 \pm 2.4)$ µas/yr

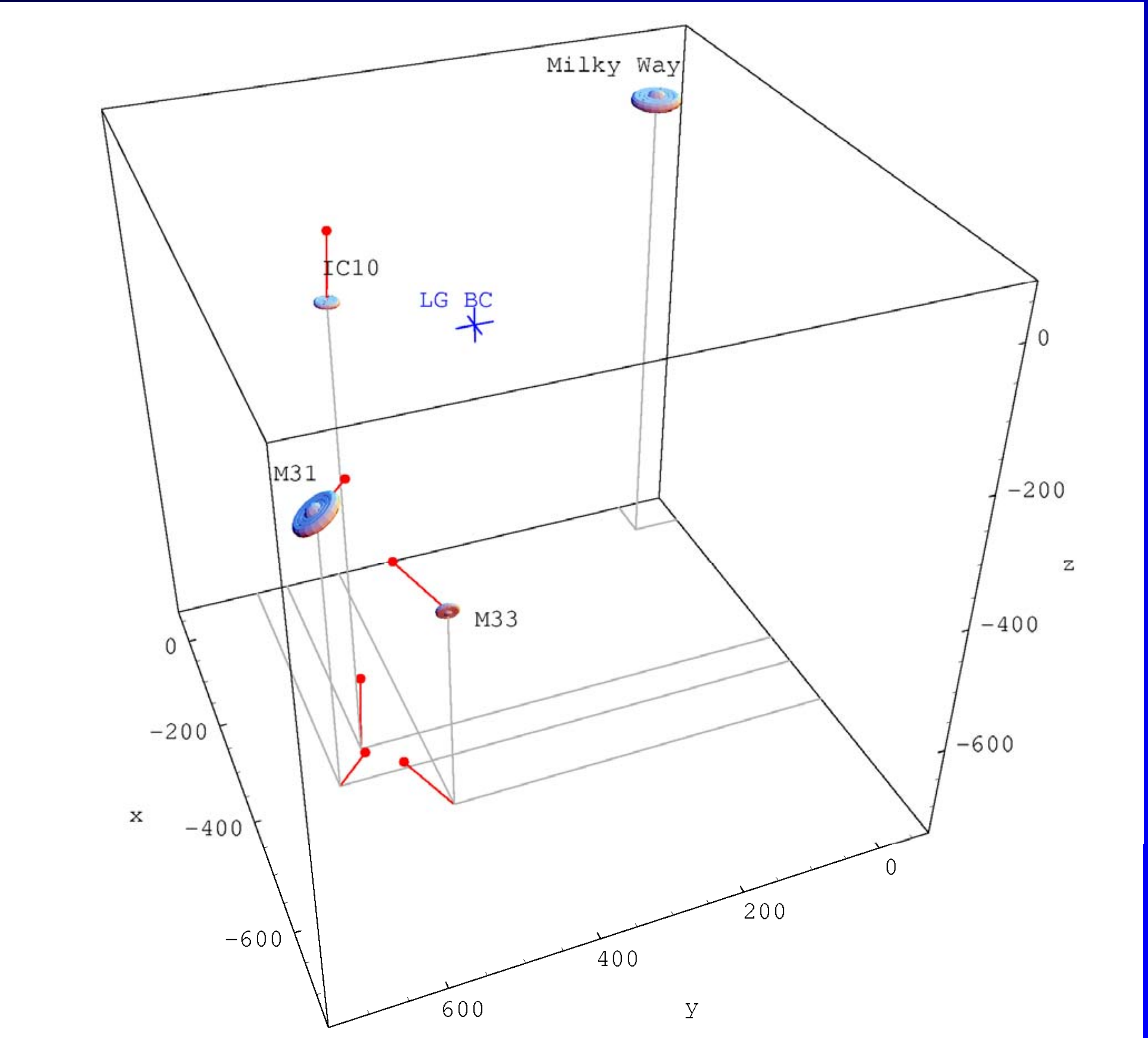
$= 45.2 \pm 9.1$ µas/yr

$= 159 \pm 47$ km/s

$v_{rad} = (-179 \pm 2) + (140 \pm 9)$ km/s

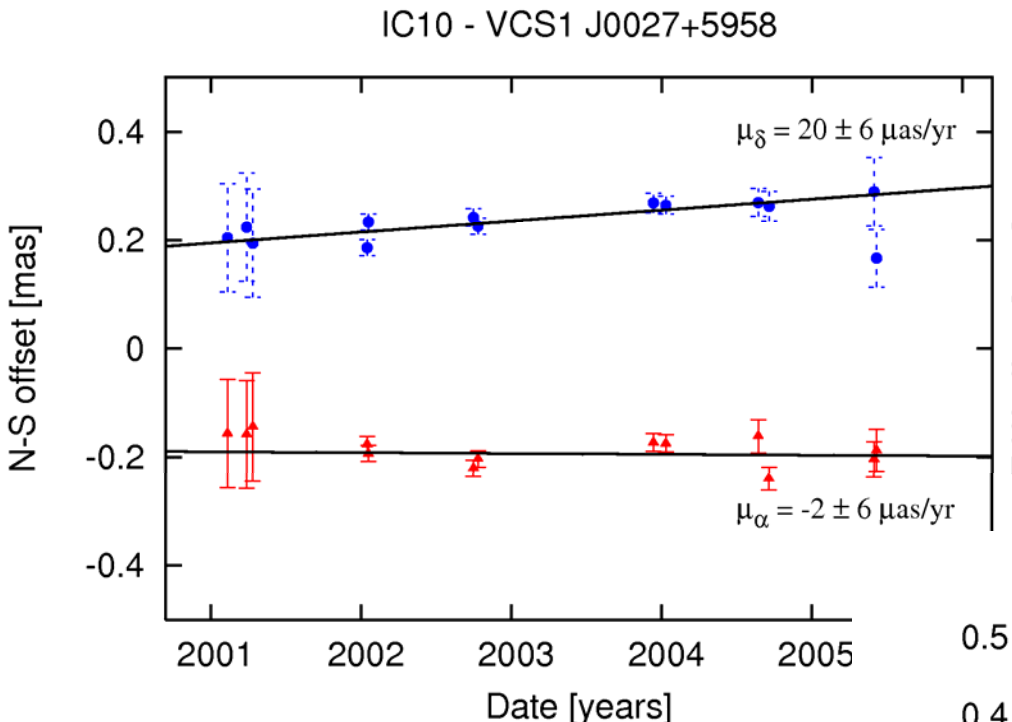
$= -39 \pm 9$ km/s

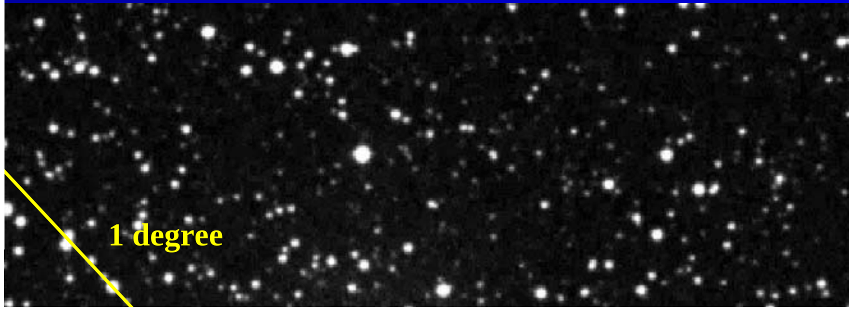
Space motion of M33

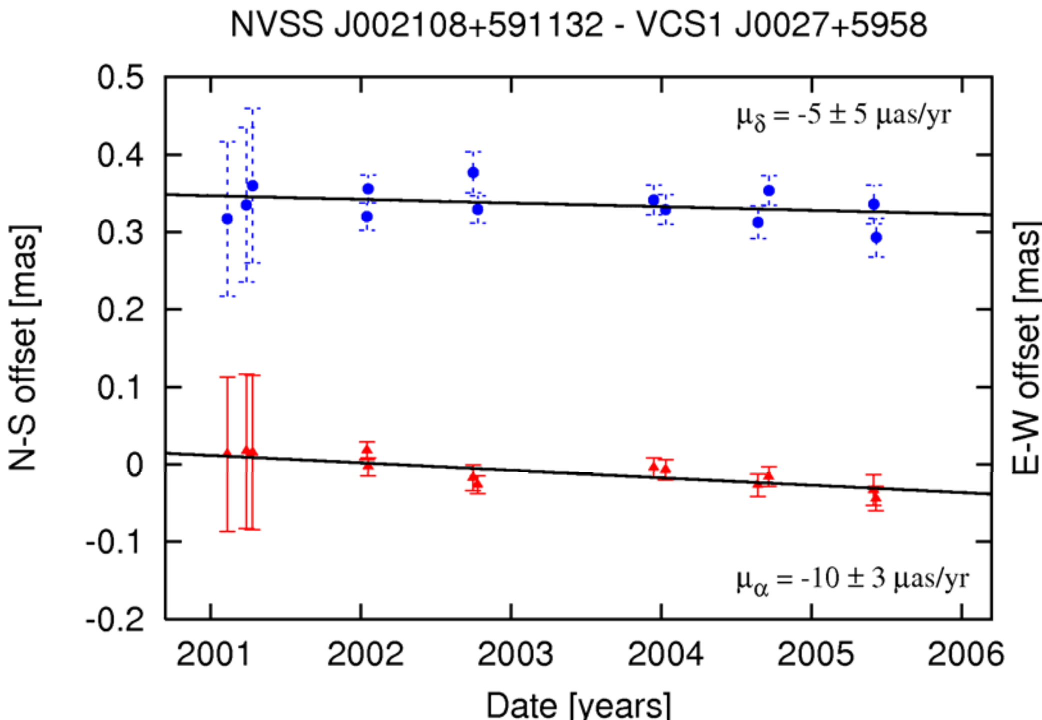


(Brunthaler et al. 2006)

Observations of IC 10

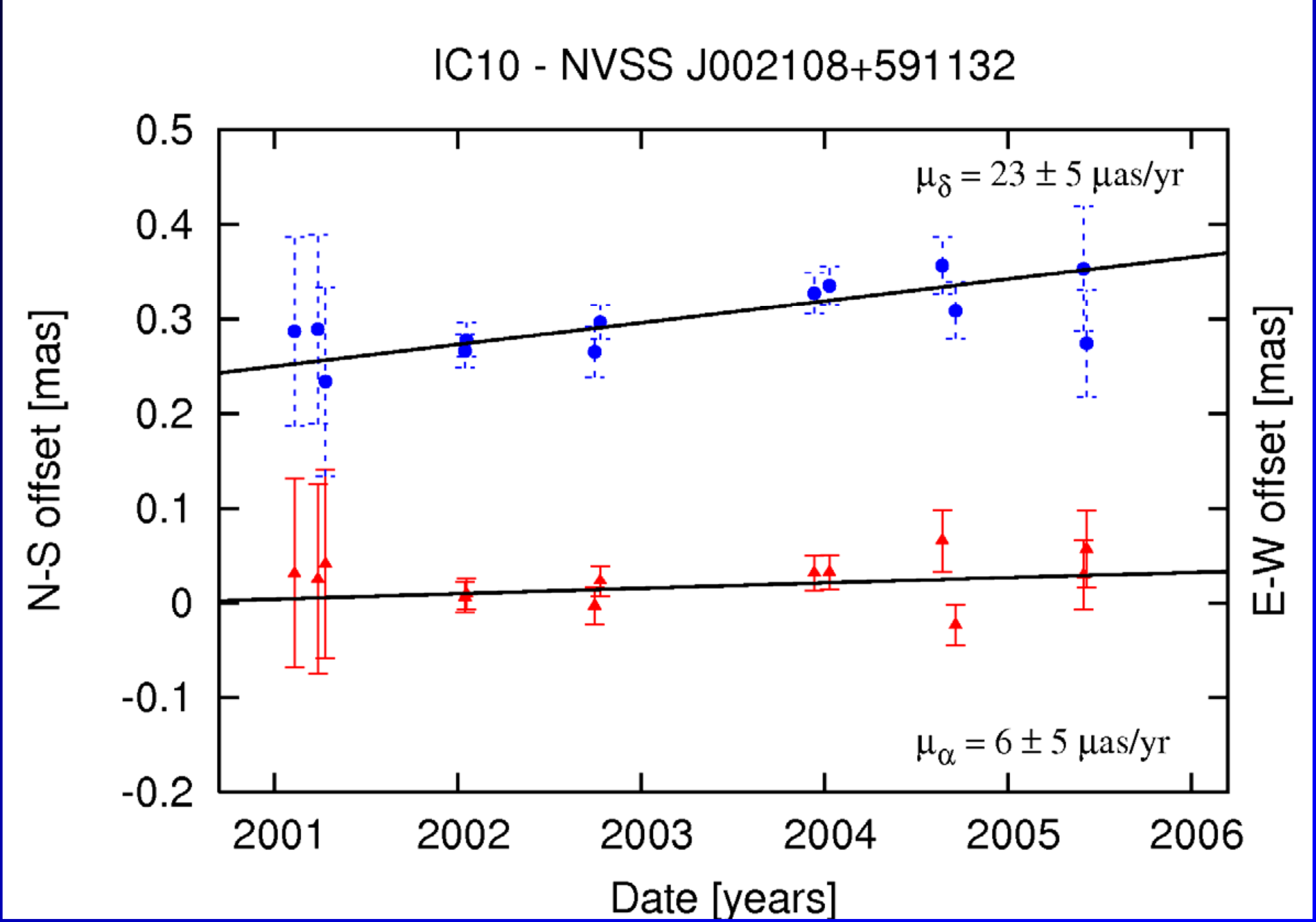






6 epochs between
02/2001 and 06/2005

Observations of IC 10



⇒ Look at relative motion between IC 10 and check source

Space motion of IC 10

- Proper motion: $\mathbf{v}_{prop} = v_{obs} - v_{rot} - v_{\odot}$

RA: $v_{prop} = (6 \pm 5) - (8 \pm 6) - (37 \pm 4)$ µas/yr

$= -39 \pm 9$ µas/yr

$= -122 \pm 31$ km/s

DEC: $v_{prop} = (23 \pm 5) - (3 \pm 6) - (-11 \pm 1)$ µas/yr

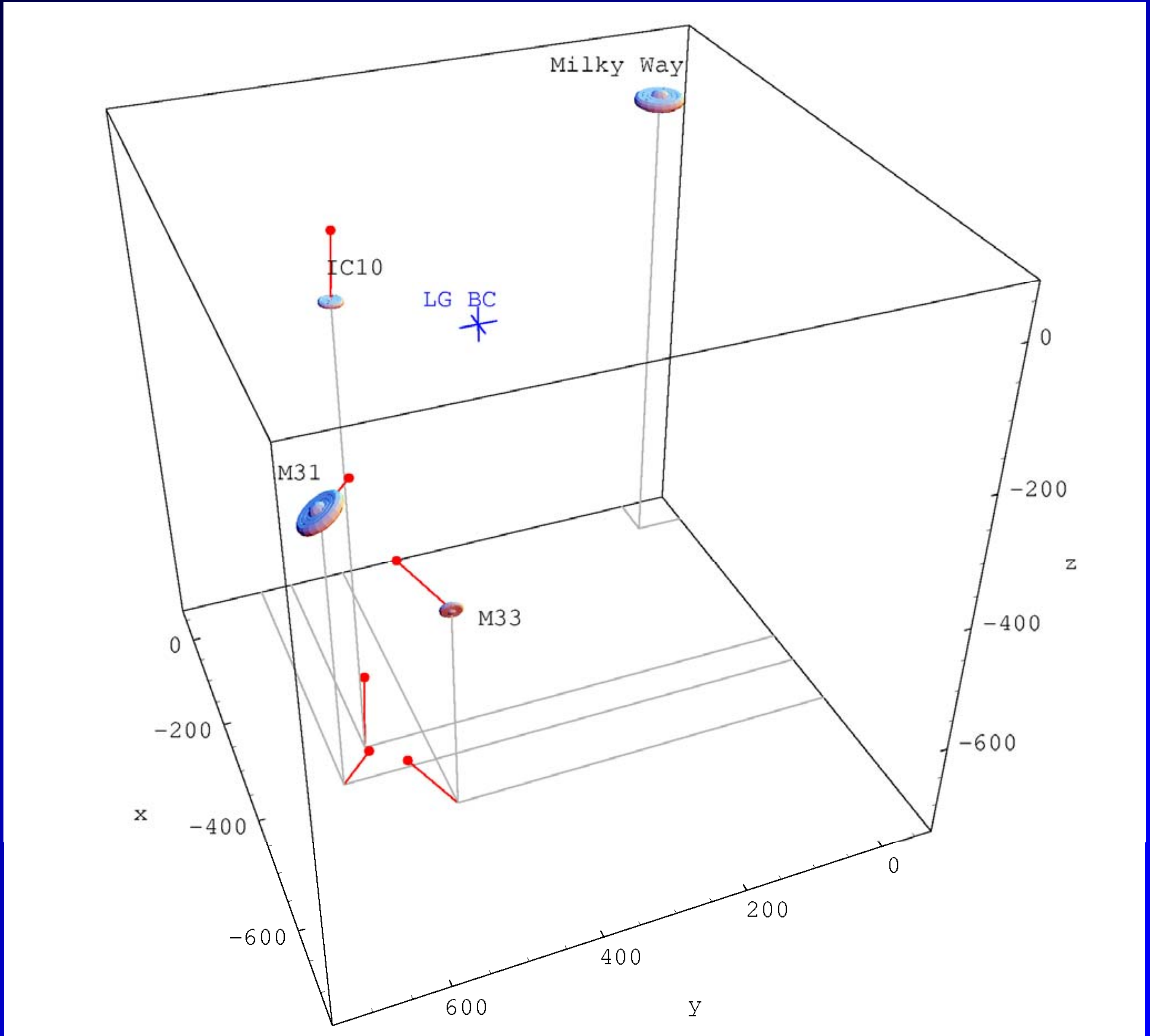
$= 31 \pm 8$ µas/yr

$= 97 \pm 27$ km/s

$v_{rad} = (-344 \pm 3) + (196 \pm 10)$ km/s

$= -148 \pm 10$ km/s

Space motion of M33 & IC 10



(Brunthaler et al. 2006)

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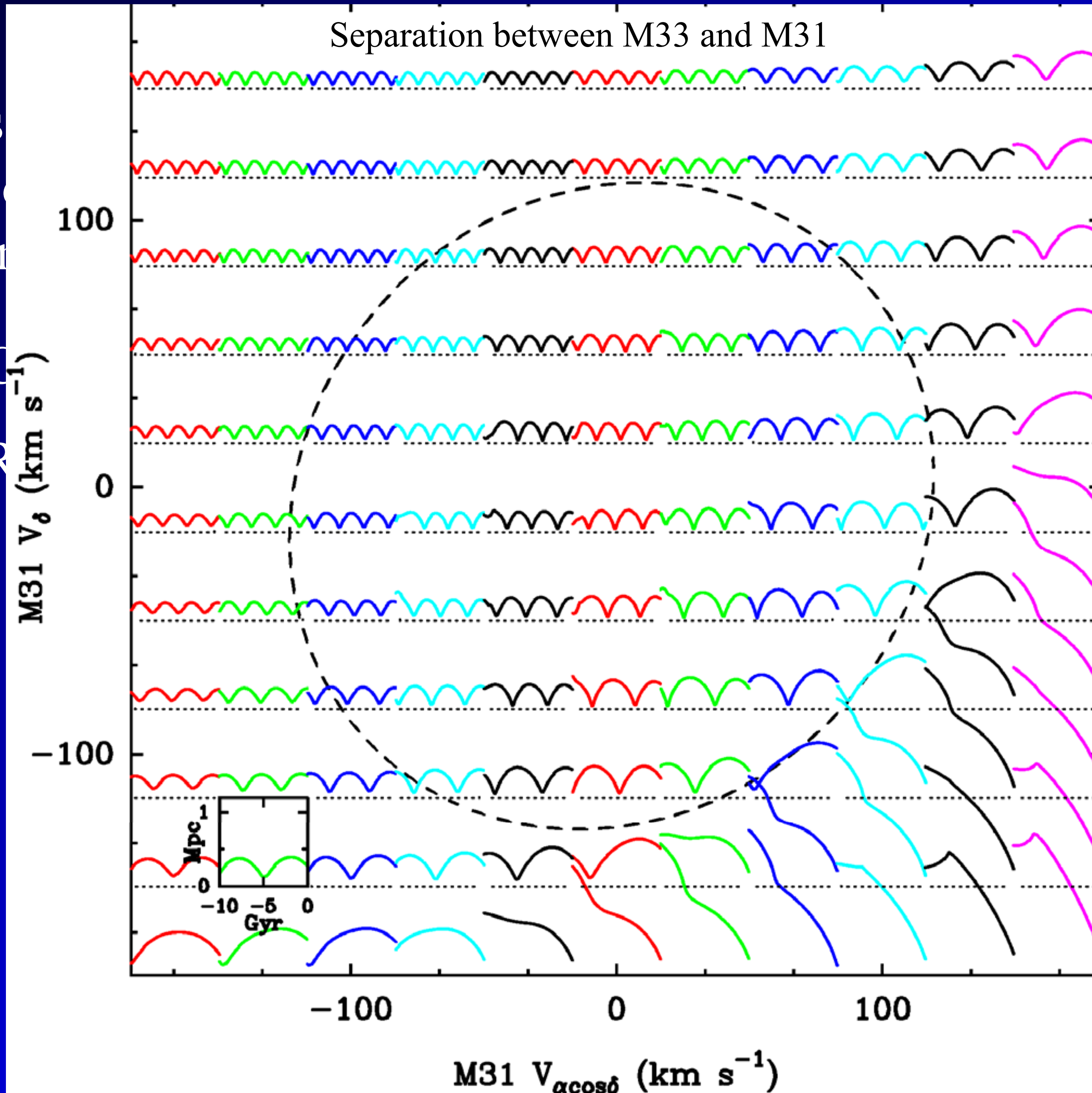
Space motion of M31

- M31's
  - n-bo
  - assu

1. C
2. R
   -



t al. 2005)

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Space motion of M31

• M31's

- n-bod ... tem

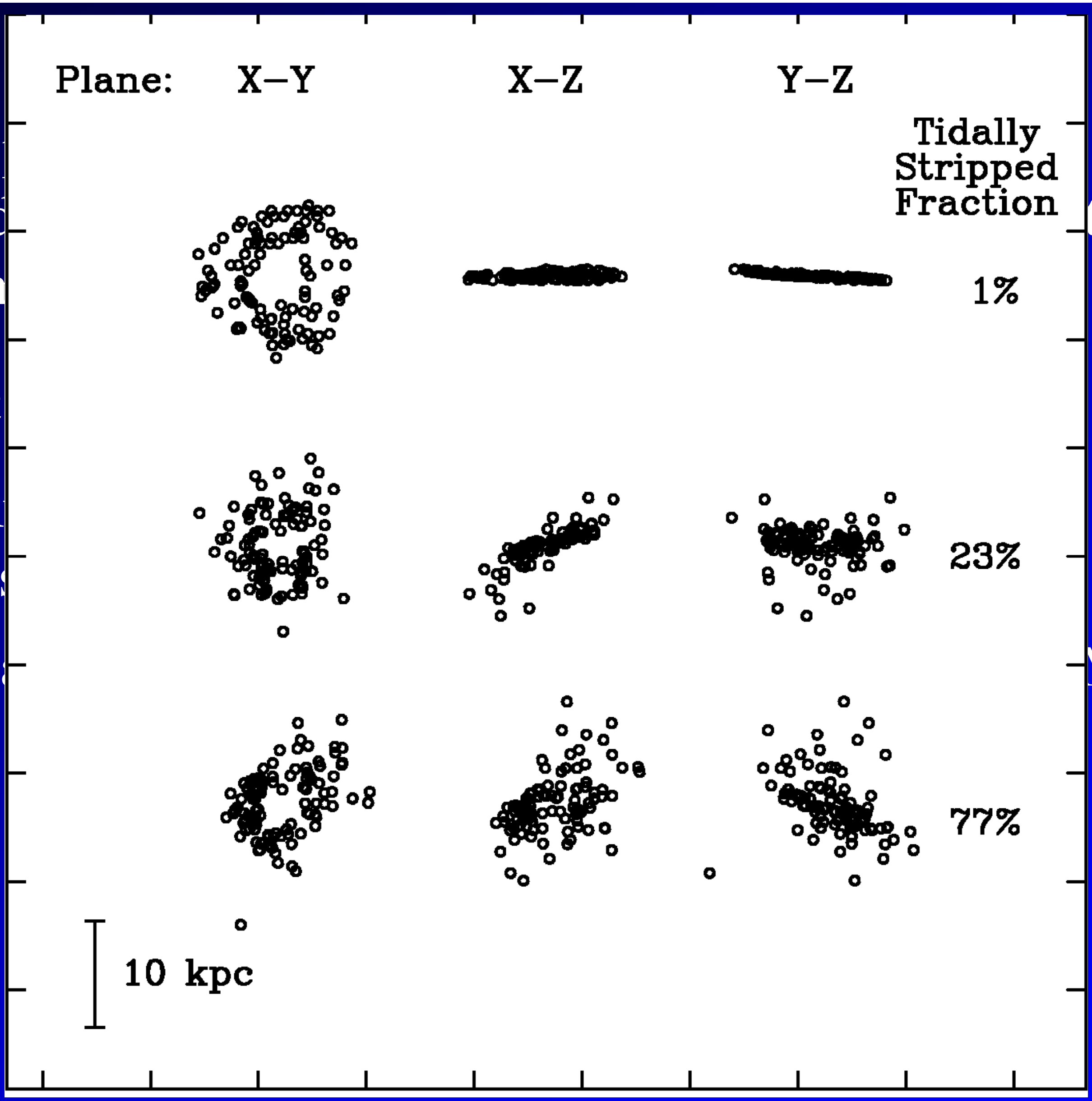
- assun

1. C

2. R

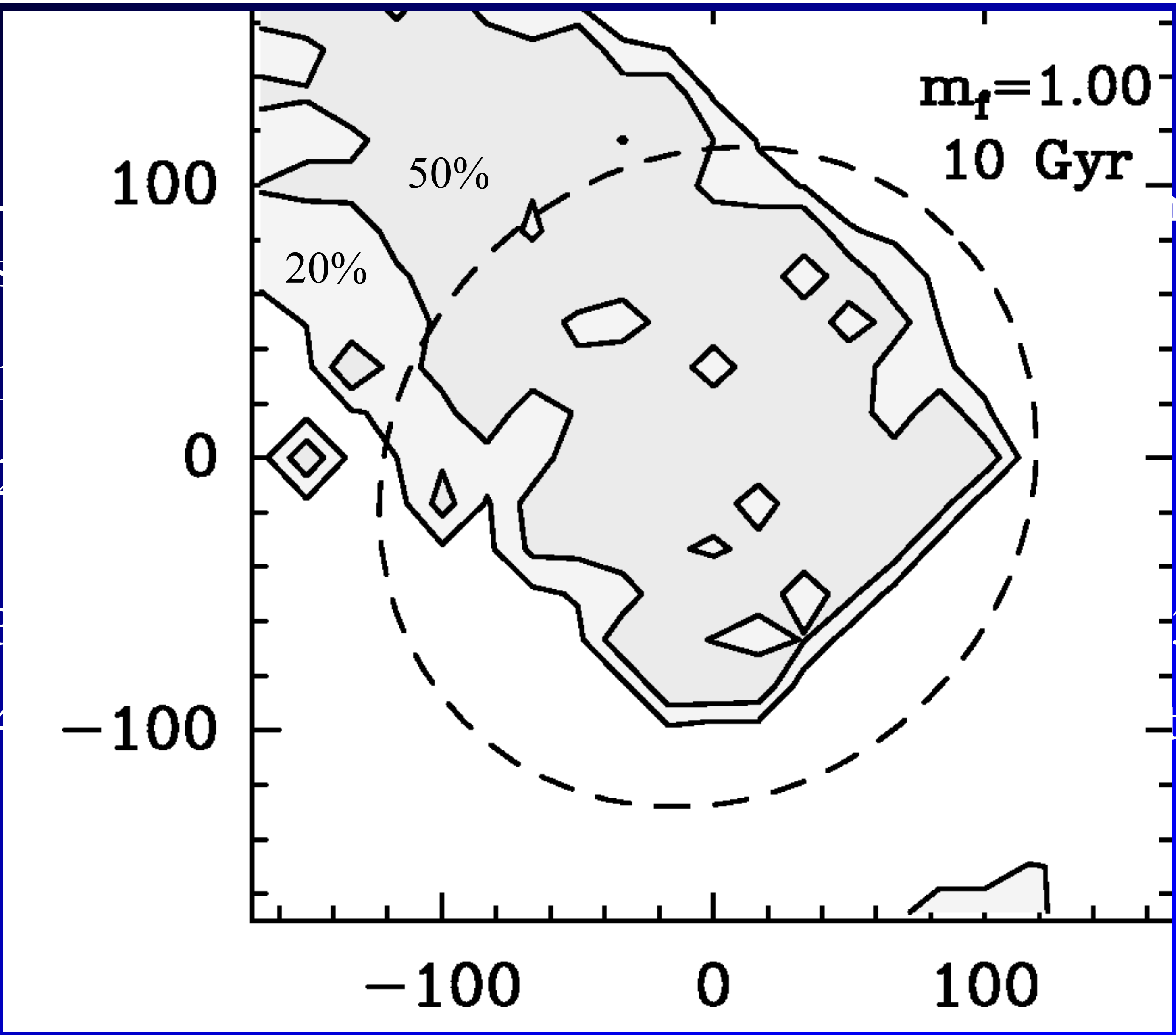
-

3. C ... M33)



(Loeb et al. 2005)

Space motion of M31



(Loeb et al. 2005)

Space motion of M31

- M31's proper motion important
  - n-body simulations of history of M33/M31/MW system
  - assume a trial proper motion for M31

1. Calculate orbits 10 Gyr backwards in time
2. Run n-body simulations forward
   - simulate M33 stellar disk with 100 tracer stars
3. Calculate fraction of tidally stripped stars (from M33)
4. exclude proper motions of M31 with a large amount of stripped stars

=> $v_{prop} > 80$ km/s

(Loeb et al. 2005)

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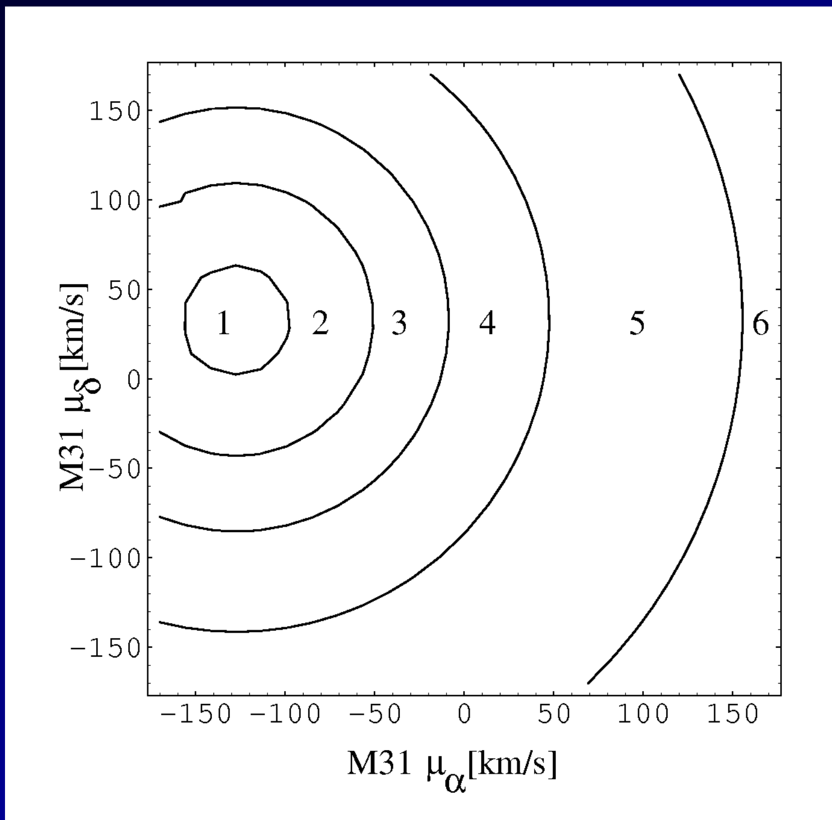
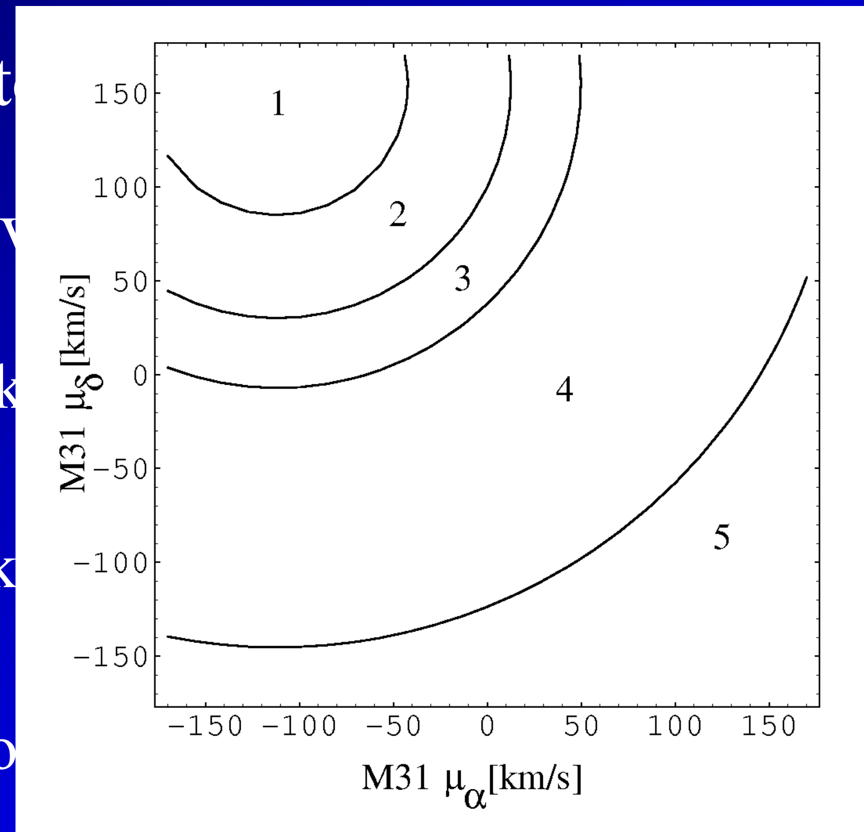
The mass of M31





Lower limits:

IC 10

$(0.7, 1, 2.5, 5, 10, 25) \times 10^{11}\ M_{sol}$

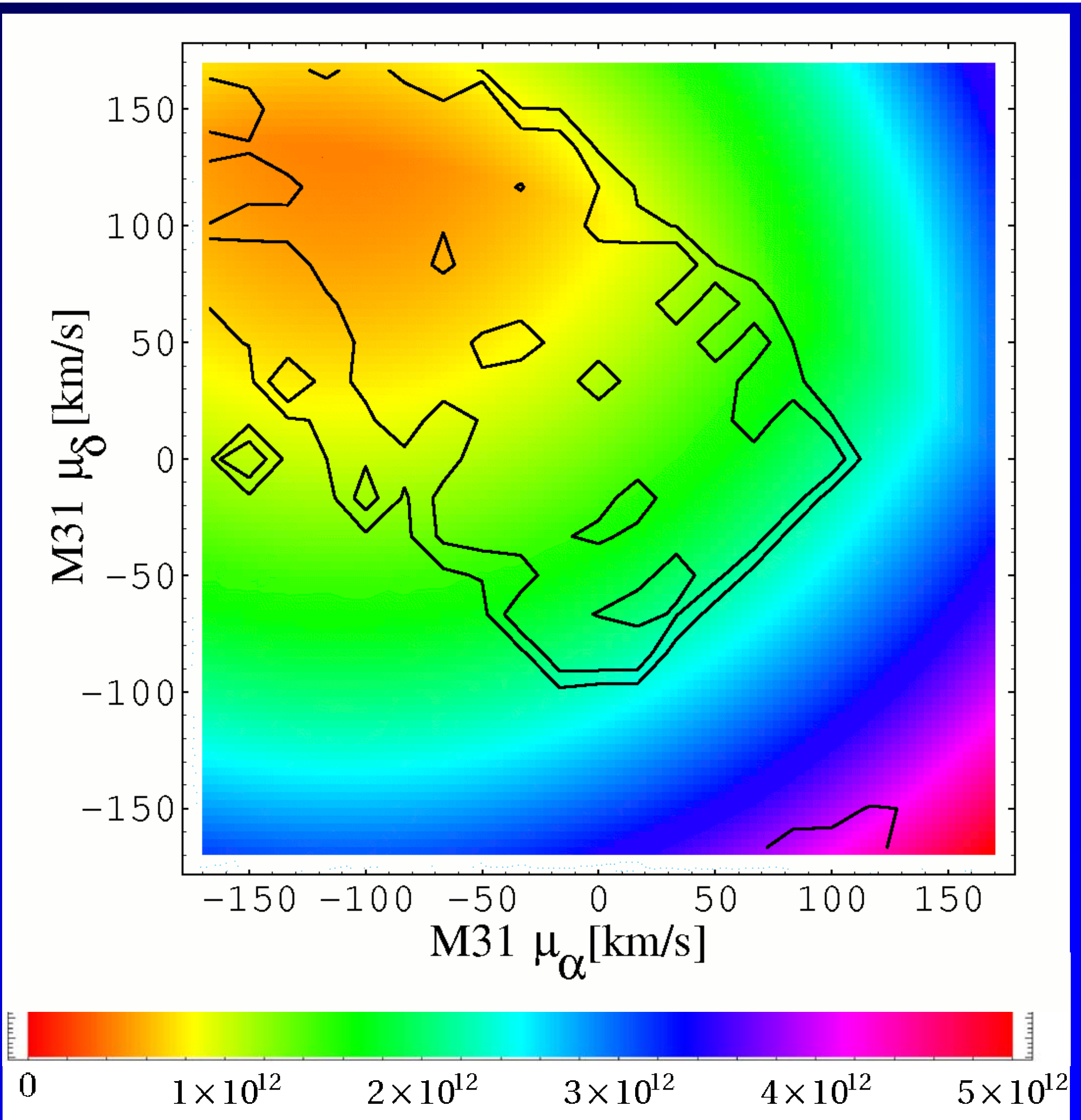
M33

$(4, 5, 7.5, 10, 25) \times 10^{11}\ M_{sol}$

The mass of M31

Combination of lower limits and excluded regions gives a lower limit

7.5×10^{11} M_{sol}



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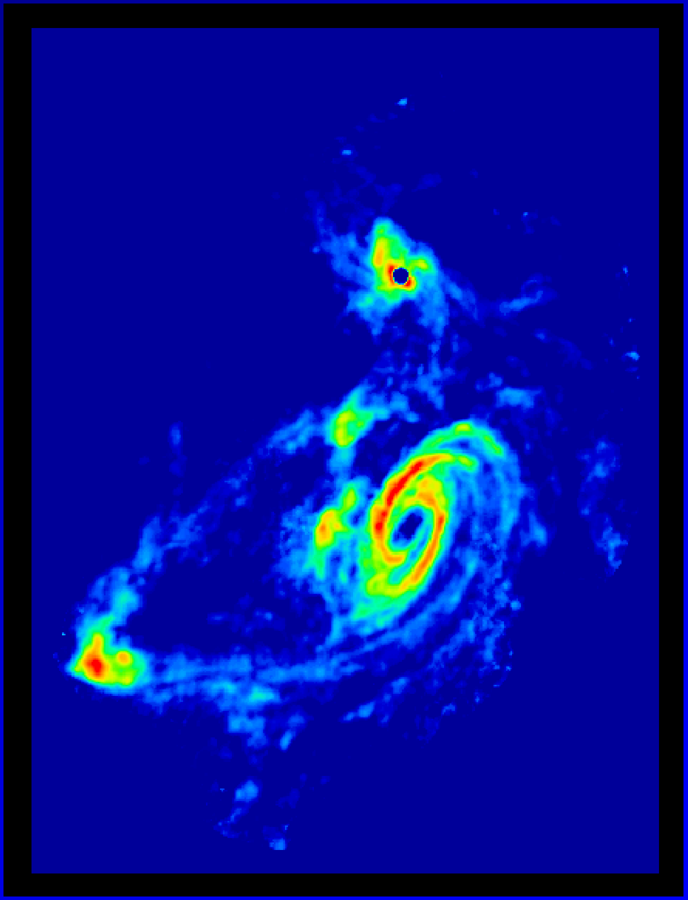
Summary

- Angular rotation of M33 measured (29.9 ± 2 μas/yr)
  - geometric distance of M33: D = 750 ± 150 kpc
  - consistent with Cepheids and TRGB
- Dynamical models of the Local Group
  - space motion of M33: $v_{M33} = 190 \pm 59$ km/s
  - space motion of IC10: $v_{IC10} = 215 \pm 42$ km/s
  - n-body simulations exclude large parameter space for motions of M31: $v_{prop} > 80$ km/s
  - total mass of M31 > 7.5×10^{11} M_{sol}

Outlook



Local Group:

- get geometric distance to M33 to < 10%
- use the (very) weak nucleus of M31
- improve simulations of the history of the

- The Local Group is not enough!

  - First epoch of M81, M82 observed last winter.
  - We will measure motions of M81 and M82 with accuracies of 30-50 km/s in the next 5 years.